Magneto-Optical Sensing of Magnetic Field

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Abstract
The non-reciprocity of magneto-optical reflection response by surface plasmon excitation in a planar glass/Fe/Au/air system with prism coupling is studied. We aim to find the optimal thicknesses of metallic layers with regard to the reflectance sensitivity to an external magnetic field. For this purpose, a corresponding response factor is introduced and applied. The numerically modeled prediction of sensitivity is verified by experimental measurements.

Keywords: Magneto-Optics, Reflectance, SPR, Response Factor

1. Introduction

Magnetic field detection based on various physical principles is quite carefully carried out [1]. If we restrict it to magneto-optical (MO) phenomena, the polarization method exploiting the Kerr rotation is among the frequently used [2,3], although it demands very fine measurement of angular changes, and requires expensive evaluation equipment. The promising possibility of magnetic field detection in surface plasmon resonance (SPR) system was briefly outlined in the Regatos et al. [4]. The connection of the MO effect with SPR is a relatively new method, when an angular shift of reflection minima rises by the polarity change of external magnetic field, if the influence of MO activity on the reflected field is not negligible.
At present, sensor elements are used that enable estimation of very small differences in optical intensity (in order 10^{-3} by normalized input) and is the reason for interest in magnetic field sensor working on a reflectometric principle. The proposed basic idea consists of a fixed incidence angle, or a relatively narrow set of items, at which the intensity of the reflected monochromatic beam is measured. Thereby the relative intensity change is proportional to the acting of outer magnetic filed on the scale between non-magnetized and saturated states by the given material parameters (permittivity, Voigt MO parameter). We discussed some theoretical aspects of this approach in our previous work [5], where the corresponding response factor and sensitivity criterion were introduced.
In the presented study we analyze some reasons why the SPR reflection minima shifts are not an optimal response factor for magnetic field detection. The more expressive response based on non-reciprocity of transversal MO effect can be described as the reflectance difference in certain interval of incidence angles. Therefore, we deal with the new factor given by the formula (5), the accessibility of which is legalized by theoretical model and experimentally as well. Finally, we propose main steps for sensor element design following the derived conclusions.

2. Theory

2.1. Model of MO-SPR system

First of all, we will characterize used optical structure for the following theoretical and experimental simulations. We consider the planar glass/ferromagnetic/gold/air multilayer with prism coupling allowing (attenuated) total reflection – see Fig. 1. The immersion layer (in the coupling gap between prism and BK-7 substrate the immersion liquid has been applied) therein serves to the optimal coupling between prism and analyzed planar MO-SPR multilayer. The more detailed description of experimental set-up can be found in the section 3. The ferromagnetic layer has no preferred crystal-graphical orientation, and all the media are homogeneous. The transverse MO configuration is supposed in all cases, the angle of incidence ϕ relates to the glass/iron interface. The *p*-polarized incidence beam is considered, so that reflectance $R_{pp} = |r_{pp}|^2$ is established as reference output parameter. The material parameters at wavelength 632.8 nm are listed in the section 3.

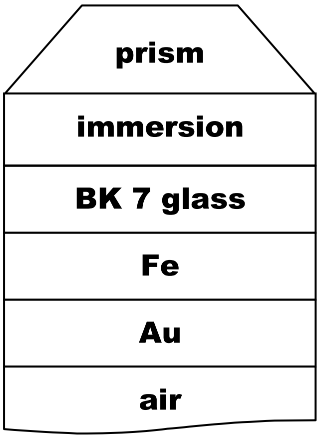

Fig. 1. Magneto-optical SPR system with immersed coupling prism (coupling gap completed by immersion liquid).

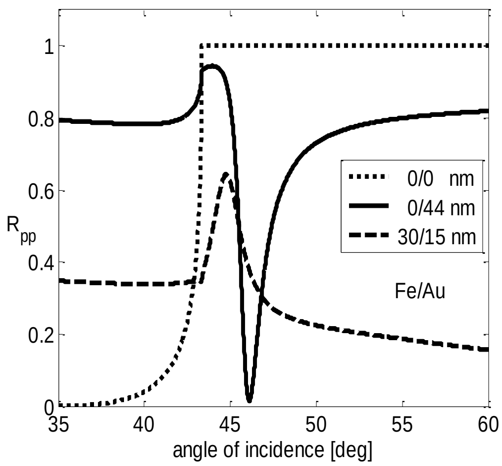

Fig. 2. Typical variants of reflection response corresponding different thicknesses of metallic layers.

Some typical reflection responses from the described optical structure are illustrated in Fig. 2. The variant 0/0 represents pure total internal reflection on the prism/air interface without absorbing losses. The next curve (0/44) with sharp resonance minima is obtained for SPR effect in 44 nm Au film deposited on a prism basis. The last case shows an influence of the ferromagnetic layer (without induced anisotropy) supplied between the prism and gold covering. As a consequence of high absorption the plasmon-resonance effect practically disappears. The gold film rather plays a protection role, because a manifold increase of its thickness has only a small influence.

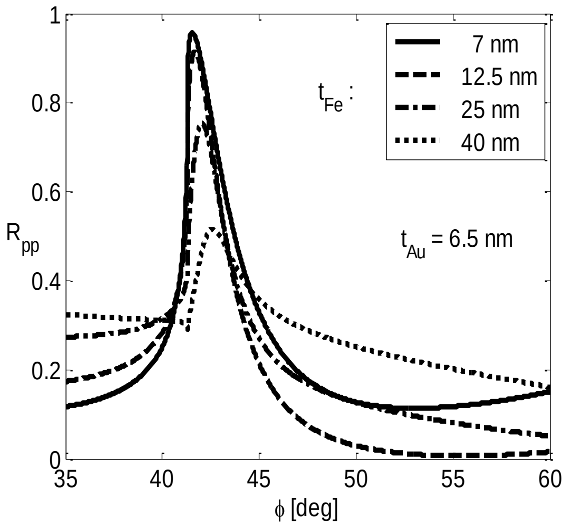

Fig. 3. An influence of iron layer thickness to the SPR response by fixed thickness of gold film.

As we aim to combine plasmon resonance with MO effect, Fig. 3 shows a more detailed view of reflection response by the fixed gold protection thickness and growing iron portion in the introduced multilayer. As we establish above, this effect leads to, among other things, shallow minima and to their flattening.

2.2. MO-SPR reflection response factors

The well-known non-reciprocity of MO-SPR reflection response observed by polarity change of the external magnetic field has been studied for various optical hetero-structures - see e.g. [6] and references therein. Obtained results confirmed bi-directionality of the MO-SPR relationship that makes the plasmon properties suitable to be altered by an external magnetic field due to MO active components of the optical system.

If we aim to exploit this principle in magnetic field sensing, then an appropriate factor of response needs be chosen that optimally represents the studied effect. As the simplest variant, we can take the angular difference of reflectance minima

$$\Delta\phi^{(\pm)} = |\,\phi(R^{(+)}_{pp,\min}) - \phi(R^{(-)}_{pp,\min})\,| \qquad (1)$$

where +/- denote conversely oriented magnetization states. Unfortunately, the minima are hardly distinguished by the presence of ferromagnetism because of their flattening due to high absorption. Moreover, this factor is very variable even by small change of metallic layer thickness that brings realization difficulties.

The other frequently used function is the ratio

$$\rho^{(\pm)}(\phi) = \frac{R^{(+)}_{pp} - R^{(-)}_{pp}}{R^{(+)}_{pp} + R^{(-)}_{pp}}\ , \qquad (2)$$

where R_{pp} is again the reflectance with signs denoting opposite directions of outer field. This quantity can achieve quite expressive extremes in the SPR minima or in their close neighborhood. The resulting effect exhibits outstanding dependence on thickness of metallic layers [7], as we can see also in the Fig. 4. Here, the values of max$|\rho^{(\pm)}(\phi)|$ are computed on the 0.5 nm grid of practically acceptable thicknesses of iron (t_{Fe}) and of gold (t_{Au}). The dimensions out of presented scales mean either the vanishing of SPR effect due to strong absorption by increasing of t_{Fe} or a lack of MO activity in the contrary case.

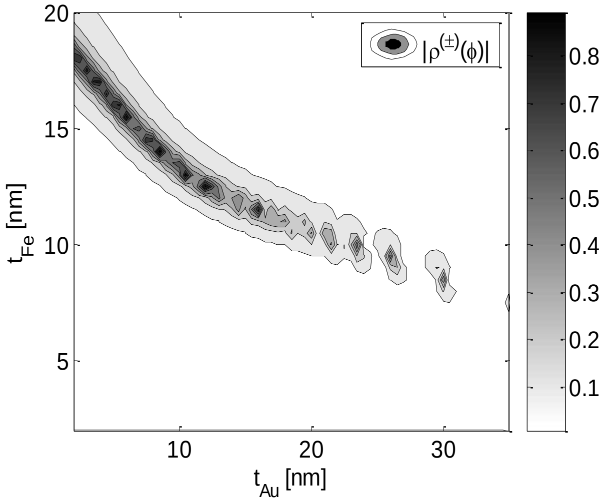

Fig. 4. Distribution of the response factor $|\rho^{(\pm)}(\phi)|$ maxima by changing thicknesses of metallic layers.

Note, that an interpretation of Fig. 4 is not unique. The high values of $|\rho^{(\pm)}(\phi)|$ for very thin ferromagnetic layer isn't caused by MO response, but the origin of them consists in a difference of sharp deep SPR minima by a conversely oriented external field. Moreover, this effect appears in model calculations unlike in experiment. On the other hand, the expected strong MO activity of structures with a greater portion of ferromagnetic (the left upper corner in the Fig. 4) is followed by remarkable absorption.

The mentioned reasons lead to the other type of response factor. Since the high sensitivity to external magnetization is unavoidable, we introduce the relation

$$\Delta R_{pp}^{(\pm)}(\phi) = | R_{pp}^{(+)} - R_{pp}^{(-)} | \ . \qquad (3)$$

Surprisingly, this function does not achieve its maxima at the reflectance extremes, but we observe its increase at a certain incidence angle between $\phi(R_{pp,\max})$ and $\phi(R_{pp,\min})$, as we established with the help of a numerical model in [5]. It is evident that quite different reflectance curves in Fig. 3 have a similar characteristic part that starts at SPR maxima and has a decreasing feature. In this range of incidence angles we aim to localize a point or thin interval with maximal MO response. The Fig. 5 demonstrates obtained results for various thicknesses of Fe film by fixed portion of Au protection (see the data in Fig. 3).

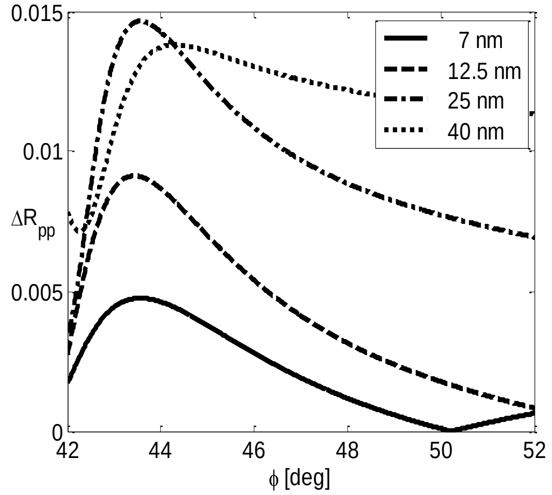

Fig. 5. Non-reciprocity of MO-SPR reflectance expressed as the difference of reflection response by Eq. (3).

In order to estimate the difference ΔR_{pp} with the required accuracy, the slope $s(\phi) = \Delta R_{pp}/\Delta\phi$ should be as minimal as possible despite the sufficiently high reflectance. In such case, the measurement stays resistant to a small change of incidence angle, what is desirable for declared aims. Mentioned properties can be expressed by the merit $\mu^{(0)}$ of the function $R_{pp}(\phi)$ in the magnetically neutral state. We introduce this in the form

$$\mu^{(0)}(\phi) = \frac{1}{2} R_{pp}^{(0)}(\phi)\left(1 + \tan\frac{|\alpha|}{2}\right), \quad \alpha = \arctan\frac{\Delta R_{pp}^{(0)}}{\Delta\phi}, \qquad (4)$$

that moves between 0 and 1, thereby the values close to 1 fulfill optimality requirement. Note that introduced merit function does not depend on the length of the chosen angular interval, which did not hold for the function used in our previous considerations [5].

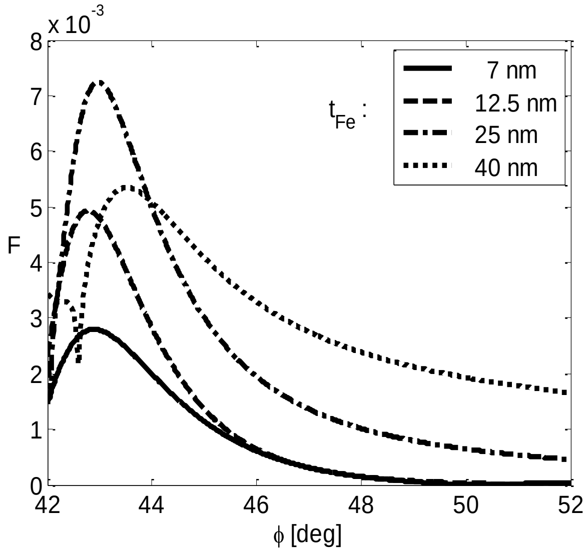

Fig. 6. The F_{max} factor variability for the same input data as in the Fig. 5 (t_{Au} = 6.5 nm).

If we supply the response function (3) by the merit defined in (4), we obtain a more truthful form of sensitivity factor

$$F(\phi) = \mu^{(0)}(\phi).\Delta R_{pp}^{(\pm)}(\phi) \quad . \tag{5}$$

Numerical simulation of this quantity at the incidence angle scale from 42 to 52 degrees is presented in Fig. 6 for the same thicknesses as in Fig. 5. The factor F reaches its maxima roughly at 43°, like as the quantity (3), but the obtained curves are more comprehensive. This observation leads to the conclusion that maximum F_{max} of the function (5) can become an appropriate factor of MO-SPR response. Its sensitivity to a thickness variance as well as to a change of incidence angles validates the stability of the proposed sensing principle regarding multilayer parameters. In section 4 we discuss the thickness influence on factor F in more detail.

3. Measurements

3.1. Experimental set-up

The measuring device Multiskop (Optrel GbR, Germany, [8]) used in our experiments was originally constructed for SPR measurements. In particular, the intensity of reflected light is detected in dependence to the incidence angle – at the wavelength 632.8 nm in our case. We completed this equipment by a digitally controlled electro-magnet with the source up to 30 A, which enables production of a predefined magnetic field of the induction up to 300 mT. Therefore, the tested samples (in transversal MO configuration) have been limited by the 10 mm width. The Fig. 7 shows the described equipment.

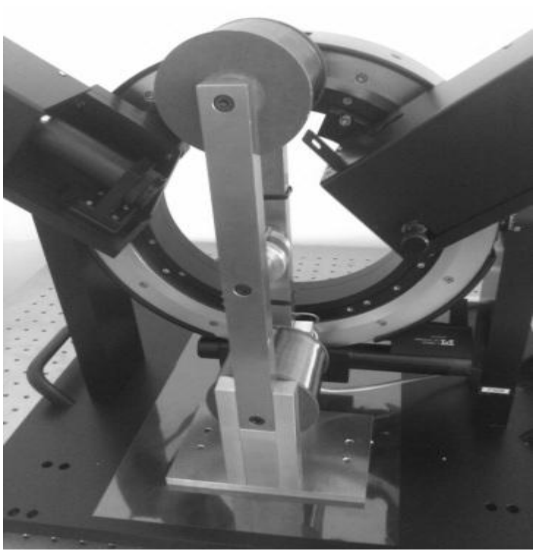

Fig. 7. The Optrel device with magnetic field source.

The Otto ordering of the basic SPR system with SiO_2 prism (vertex angle 90 deg) was applied (Fig. 1), where the immersion liquid was of the same refraction index as the coupling prism.

3.2. Samples

As the base of samples, the 1.1 mm thick glass plate (BK7) was used, from which the rectangular substrates (10 × 80 mm regarding to the implemented electro-magnet) were prepared and cleaned by alcohol. The metallic bi-layers were deposited successively without interruption in the vacuum chamber (Leybold Heraeus Z550): the pressure 0.2 Pa and power

of 150 W by iron, 0.2 Pa / 75 W for the gold protect deposition. The process ran in an oscillating regime with exactly 0.5 nm deposition step in any period.
Finally, three samples with different metallic compound were chosen for testing for magneto-optical reflection response – see Table 1.

Tab. 1. Metallic layers in samples.

Sample	Thickness [nm]	
	Fe	Au
No. 1	7.0	31.5
No. 2	12.5	6.5
No. 3	11.0	11.0

The ferromagnetic layer had no preferred crystal-graphical orientation; the data presented for metallic layers were confirmed by magneto-optical fitting by differential intensity method. Surface hysteresis loops are measured in longitudinal configuration, when the magnetization component in the plane of incidence and sample is parallel to the applied magnetic field. The whole set-up consists of a red laser diode working at a wavelength of 670 nm, the photo-elastic modulator, the quarter-wave plate for Kerr ellipticity measurements, the Wollaston prism and two Si photodiodes. Optical and magneto-optical parameters of Au/Fe systems were obtained from angular dependence of both Kerr angles at incident *s* and *p* polarized light. Measured data were compared with the model based on propagation of light in thin anisotropic films. Obtained results correspond sufficiently to those published in [10]. The graphical outputs are presented in Figs. 8 and 9.

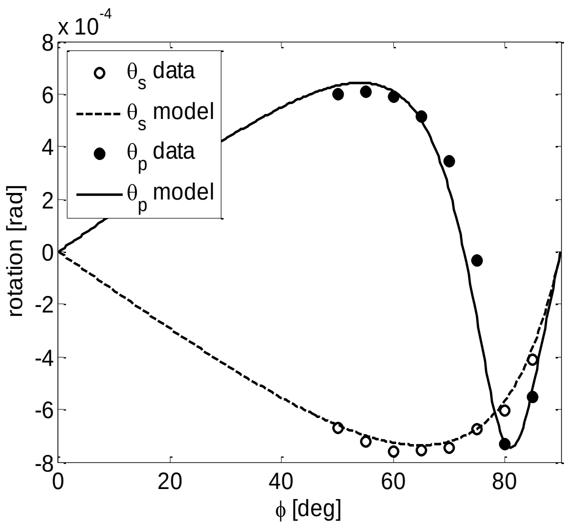

Fig. 8. Kerr rotation – sample no. 2.

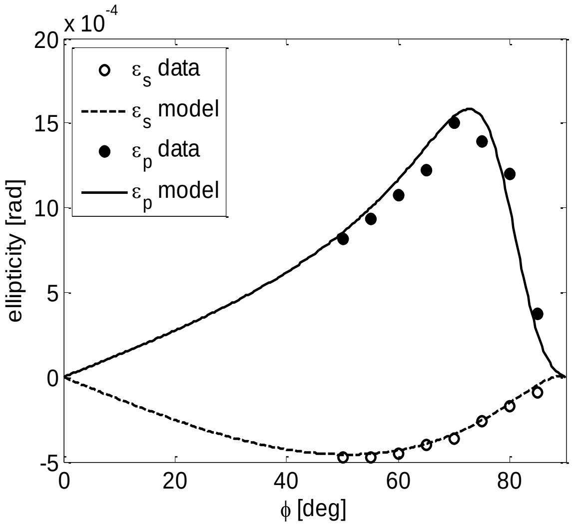

Fig. 9. Kerr ellipticity – sample no. 2.

For the MO-SPR reflectometric experiments the material characteristics were established at wavelength 632.8 nm as follows: n_p = 1.4571 (fused silica prism [9]), n_g = 1.5146 (BK7 glass plate [9]), n_{Au} = 0.1911 – 3.3577i [10], n_a = 1 (air), ε_{Fe} = -1.0365 -17.7672i, q_{Fe} = 0.0386+0.0034i [10]. Here, n denotes a refractive index, ε is the relative permittivity and q is the Voigt parameter.
Since the measurements were obtained at non-equidistant angular scale (with steps less than 0.01°), the additional four-parameter exponential re-sampling

$$R_{pp}(\phi) = c_1 \exp(r_1\phi) + c_2\phi\exp(r_2\phi) \qquad (6)$$

was executed in the case of the samples 2 and 3. For sample 1, the polynomial pre-processing appeared to be more effective.

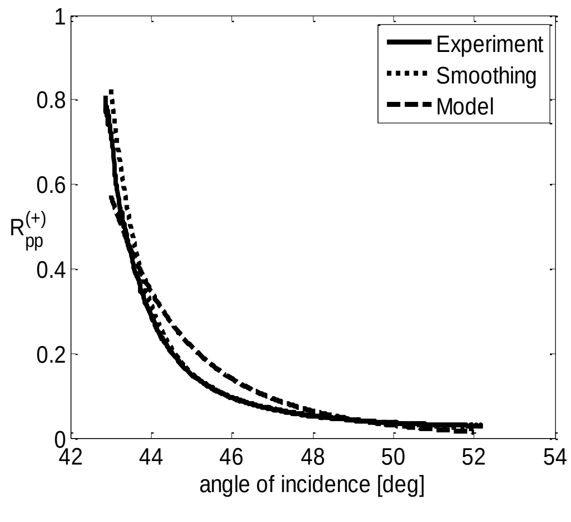

Fig. 10. Measured vs. computed reflectance (sample no. 2, magnetization +); the dotted line represents smoothed experimental data.

As an example, the output (dotted line) is compared with source data and with model calculation in Fig. 10. Here, as well as in the following examples, the incidence angle corresponds to the glass plate – iron interface. A difference between the numerical model and experimental data should be acceptable with regard to uncertainness in the material parameters of metals estimate.

4. Results and discussion

4.1. MO-SPR sensitivity of samples

The response factor *F* introduced by Eq. (5) has been calculated for the described samples at the incidence angles between estimated reflectance maxima and minima. Obtained results in Fig. 11 demonstrate expected weak MO sensitivity of sample No. 1 due its low ferromagnetic content. On the other hand, the factor *F* by the other two samples exhibits sufficiently representative maxima at the close values of the incidence angle (see Tab. 2).

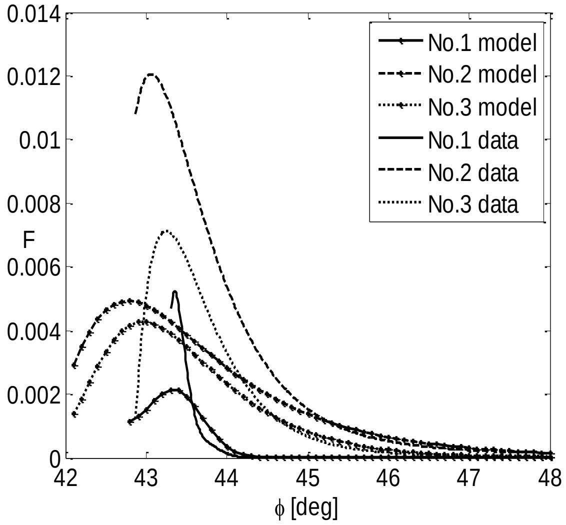

Fig. 11. Response factor *F* – modeled vs. experimental results.

The numerical model realized by a rigorous coupled wave algorithm (RCWA) gives very similar output that confirms provided measurements – see marked curves in the Fig. 11 and the data in Tab. 2.

Tab. 2. Global maxima of response factor *F* – experiments vs. theoretical prediction.

No.	$\phi(F_{max})$ [°]		F_{max}	
	Exp.	Num.	Exp.	Num.
1	43.35	43.33	0.0052	0.0021
2	43.06	42.78	0.0121	0.0049
3	43.25	42.96	0.0071	0.0043

As demonstrate the results summarized in Tab. 2, angular agreement of measured and computed data is very good, but the experimental values of F_{max} are approximately two times greater. A possible explanation of this fact can follow from a lack of gold protecting planarity, the origin of which is the preparation technique of samples with extremely thin nano-layers.

4.2. Optimal MO-SPR sensitivity

In order to obtain the information about distribution of the MO response maxima depending on metallic layers thicknesses, we calculated the maxima of factor *F* on the fine grid with 0.5 nm step for the appropriate range (5-35 nm) of thicknesses. The result visualized in Fig. 12 shows that the variability of response maxima is very slow, and, the influence of protecting Au film is less remarkable than that of the Fe layer.

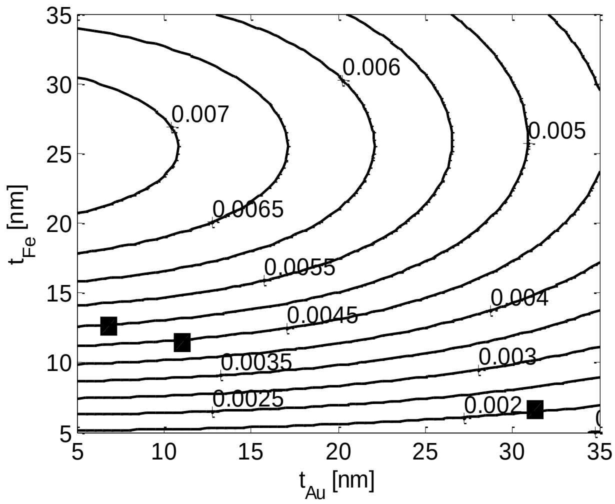

Fig. 12. Contour plot of the factor *F* maxima. Black squares are placed at points representing tested samples.

Optimal thicknesses of metallic layers appear close to 25 nm of ferromagnetic and 5-10 nm of Au film. Moreover, numerical simulation in Fig. 13 shows that the values of $\phi(F_{max})$ move slowly at about 43°. These very small deviations of F_{max} as well as of corresponding incidence angles validate the stability of the described sensing method regarding multilayer parameters.

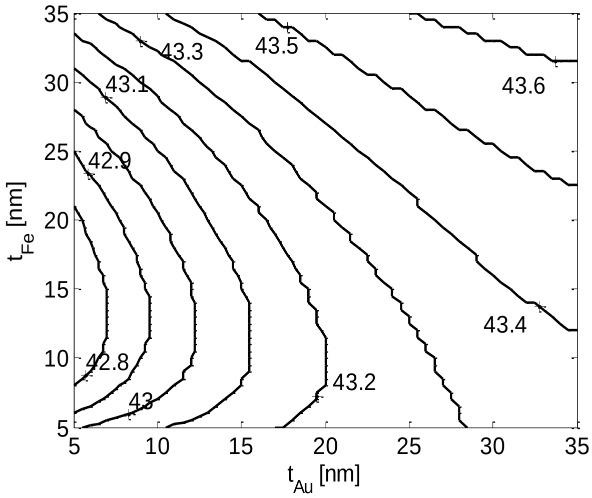

Fig. 13. Contour plot of the incidence angles $\phi(F_{max})$ corresponding to the F_{max} data in the Fig. 12.

4.3. The proposal of magnetic field sensor

Since the realized experiments confirmed supposed sensitivity properties, we can attend to the proposal of magnetic field sensor based on the combination of magneto-optical and plasmonic parameters of studied optical structures. Thus, the following design steps of suitable sensing device should be recommended:

- the proposal of Fe and Au thicknesses with regard to optimality condition $F_w = \max(F_{\max})$ for sensitivity factor F,
- after a sample preparation, together with experimental and theoretical verification, an improvement of operating incidence angle $\phi_w = \phi(F_w)$ or a set of items.

As follows from the presented study, the governing parameters as $F_{\max}$ and $\phi(F_{\max})$ of a proper MO sensing element are sufficiently resistant to small changes of metallic layers thicknesses that permits several nanometers of construction tolerance without loss of accuracy.

5. Conclusions

We have demonstrated that in the frame of the strategy related to magnetic field sensor construction based on reflected polarized light response from MO-SPR system the reflectance minima shift principle is not able. The new type of response factor F was introduced that takes into account both magneto-optical activity and reflection properties of studied optical nanosystems. As regards the global maxima of the response factor F, the angular agreement of experimental and computed data is very good. It means that this response factor can be used in the frame of material and geometrical optimization processes in MO-SPR sensor preparation.

Acknowledgements
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